Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Improvement Plans of Fermilab's Proton Accelerator Complex

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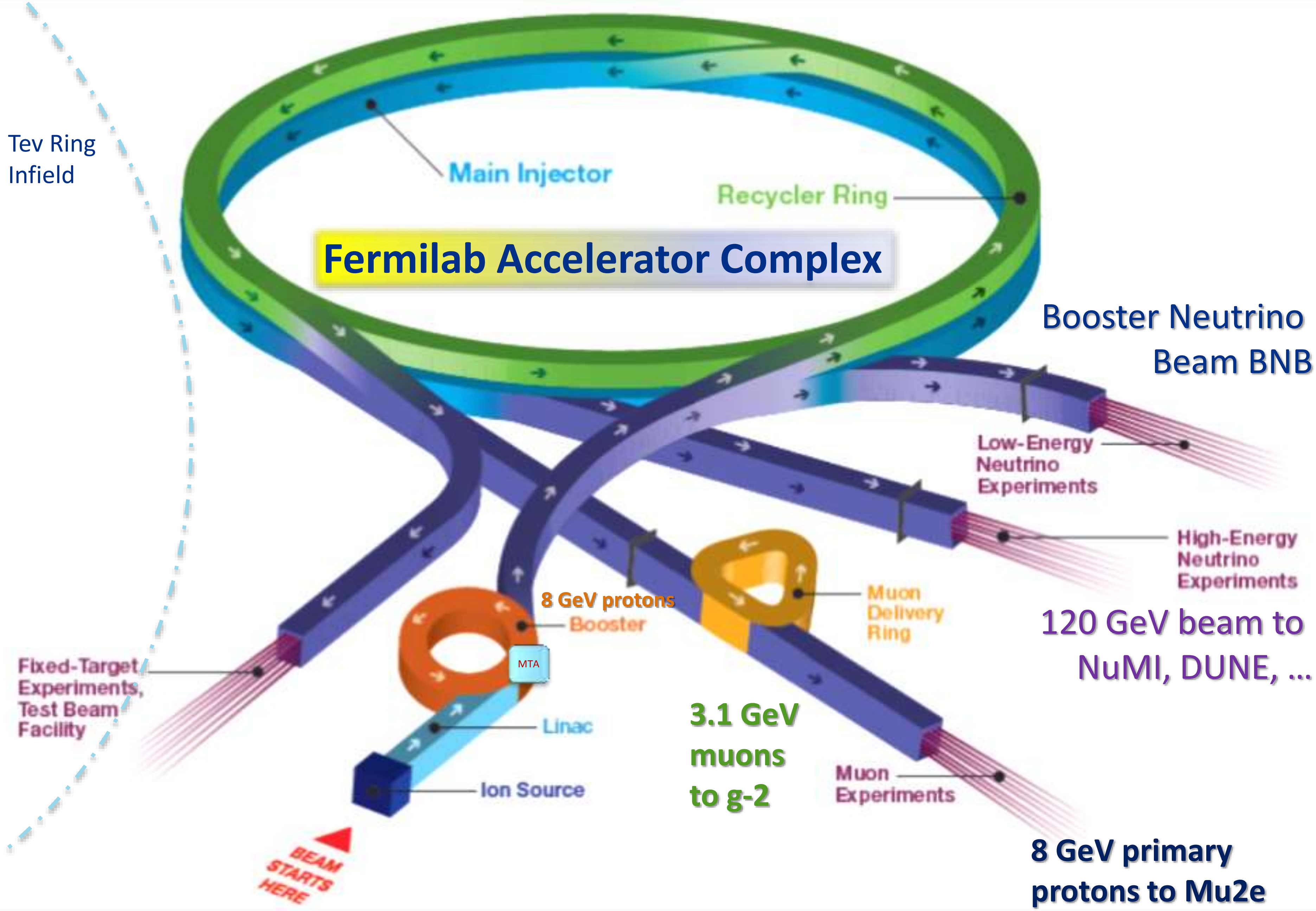
"Neutrino – 2016"

London, 9 July 2016

* Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy

Fermilab Complex : 16 km of accelerators and beamlines, two high power targets, several low power target stations…

Fermilab Accelerator Complex

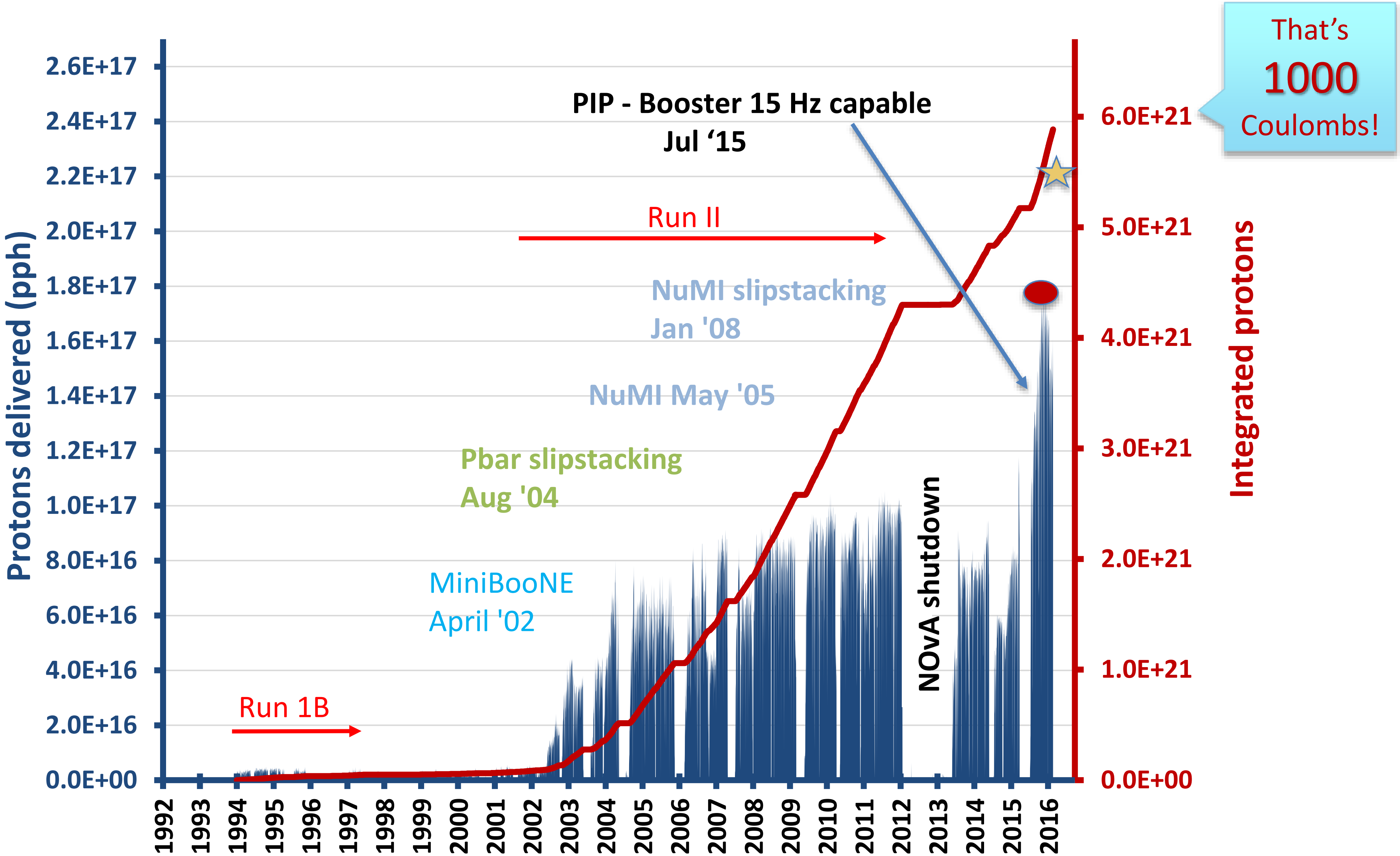


Fermilab Accelerator Complex Users

- Proton Source (**400 MeV** Linac and 8 **GeV** Booster ring):
  - 8 GeV Booster Neutrino Beam (BNB)
    - ANNIE
    - MicroBooNE
    - MiniBooNE
    - MITPC
    - SciBath
    - ICARUS (future)
    - SBND (future)

    8 GeV proton program expanding
  - Mucool Test Area (MTA, **400 MeV** beam test facility)
- **120 GeV** Main Injector / **8 GeV** Recycler:
  - NuMI: MINOS+, MINERvA, NOvA
  - LBNF/DUNE (future)
  - Fixed Target: SeaQuest, LArIAT, Test Beam Facility
  - Muon: g-2, Mu2e (future)

Historic Proton Source Flux Plot



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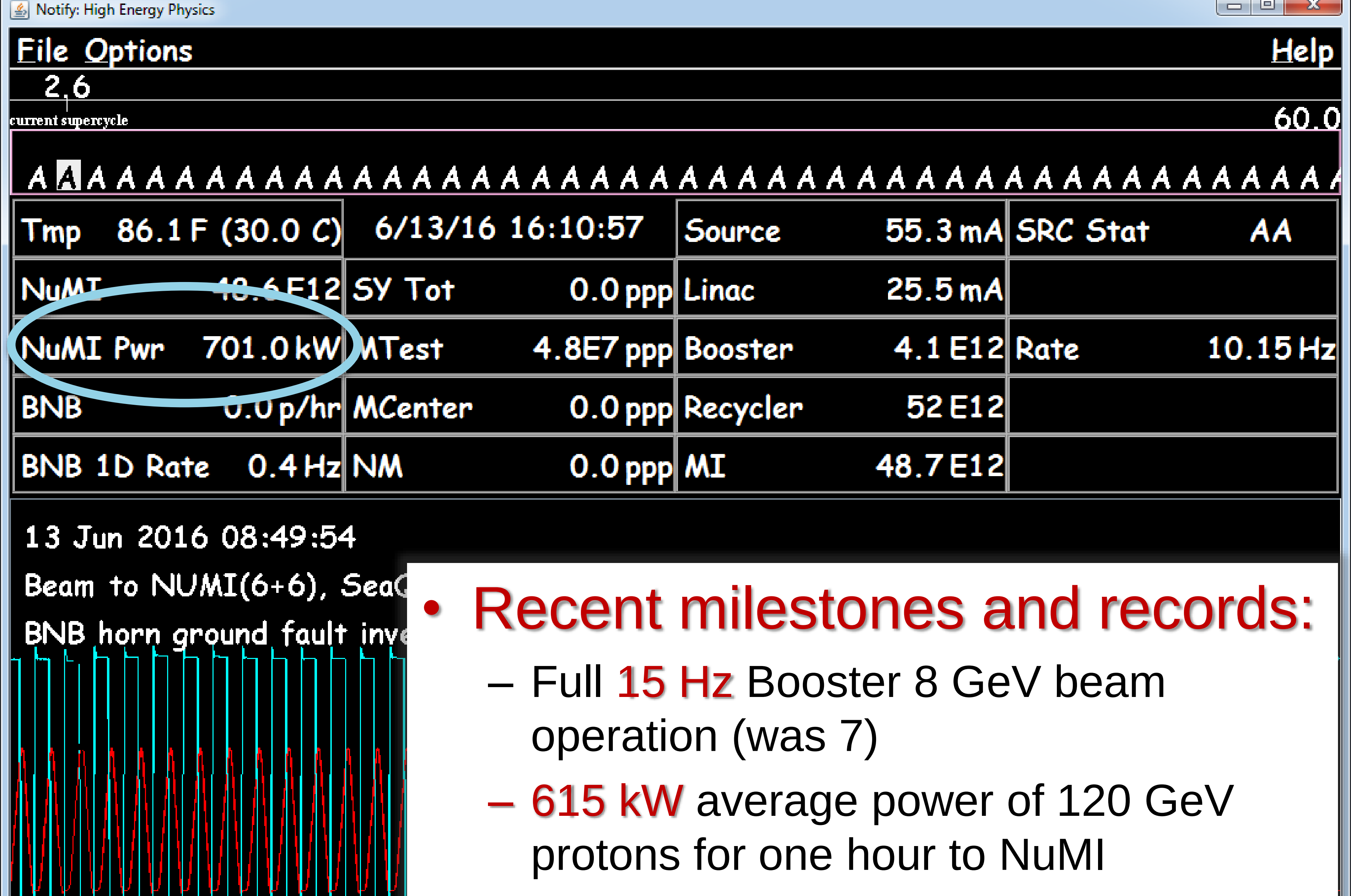
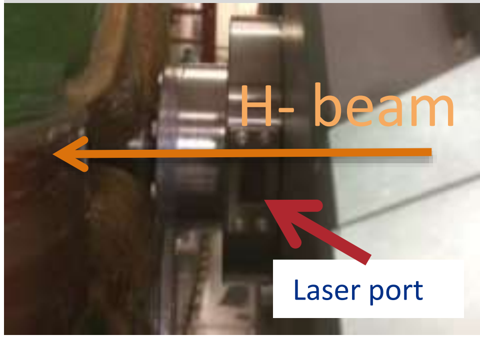


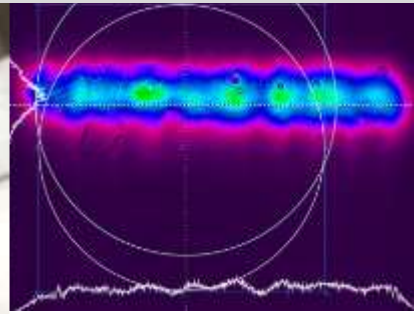
- Recent milestones and records:
  - Full 15 Hz Booster 8 GeV beam operation (was 7)
  - 615 kW average power of 120 GeV protons for one hour to NuMI

  ← 700 kW for 1 minute (restricted by losses in Recycler)

Current Proton Improvement Plan (PIP)

Laser Notch System in Ion Source
(Vacuum box installed RIL)

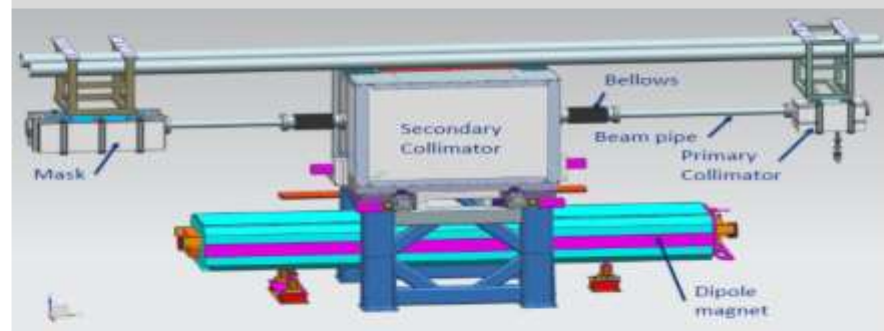




Refurbishment of old 37-53 MHz RF cavities and tuners in 8 GeV Booster RCS

New 35kV Marx Modulators for 400 MeV LINAC

(Summer 2016) Installation of collimation system in 8 GeV Recycler



in 2017 routine

700 kW beam to NuMI target

Fermilab: always changing to meet the needs of the users…

← 1967 photo: Breaking ground for our national HEP program (Linac)

FY17 looks to be as productive with even higher flux for the neutrino experiments and *g-2* beam startup→

Accelerators for Neutrino Research

300+ kW JPARC (Japan) 30 GeV

400+ kW CNGS (CERN) 400 GeV

600+ kW Fermilab's Main Injector (2016) 120 GeV

EVOLUTION OF INTENSITY FRONTIER ACCELERATORS

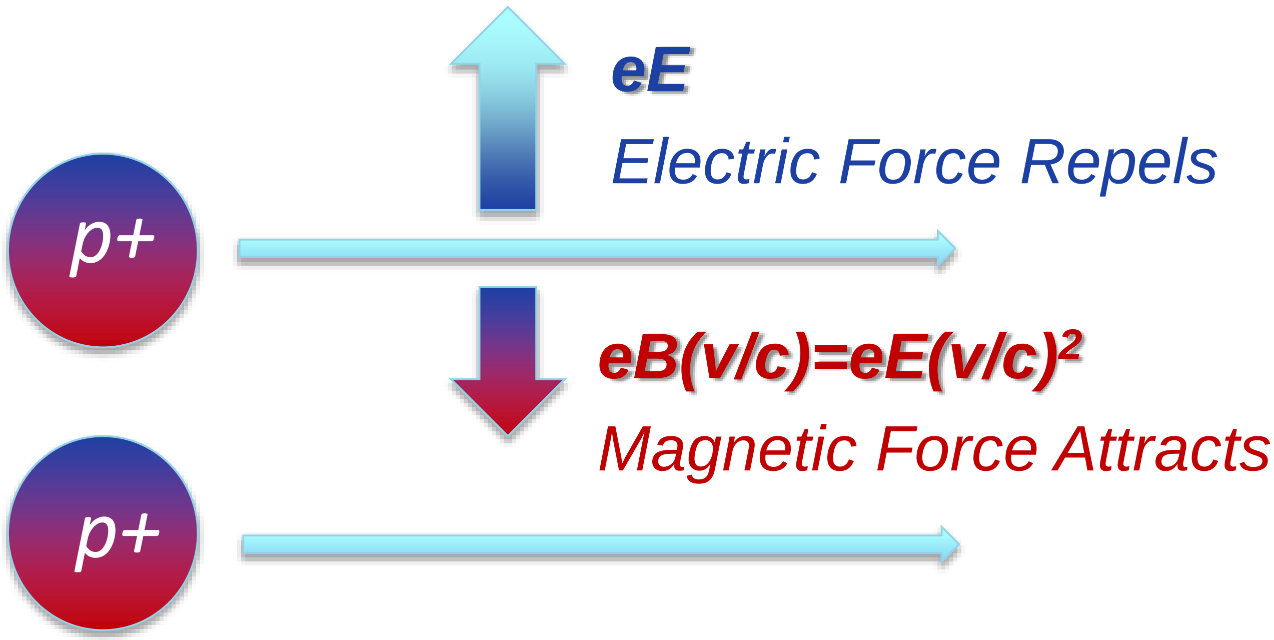
700+ kW Proton Improvement Plan (PIP, 2017)

1.2+ MW Proton Improvement Plan-II (ca 2025)

2.5 MW → 5 MW?

Plan for multi-MW Upgrade (under study)

Intense Beams : Forces and Losses (1)

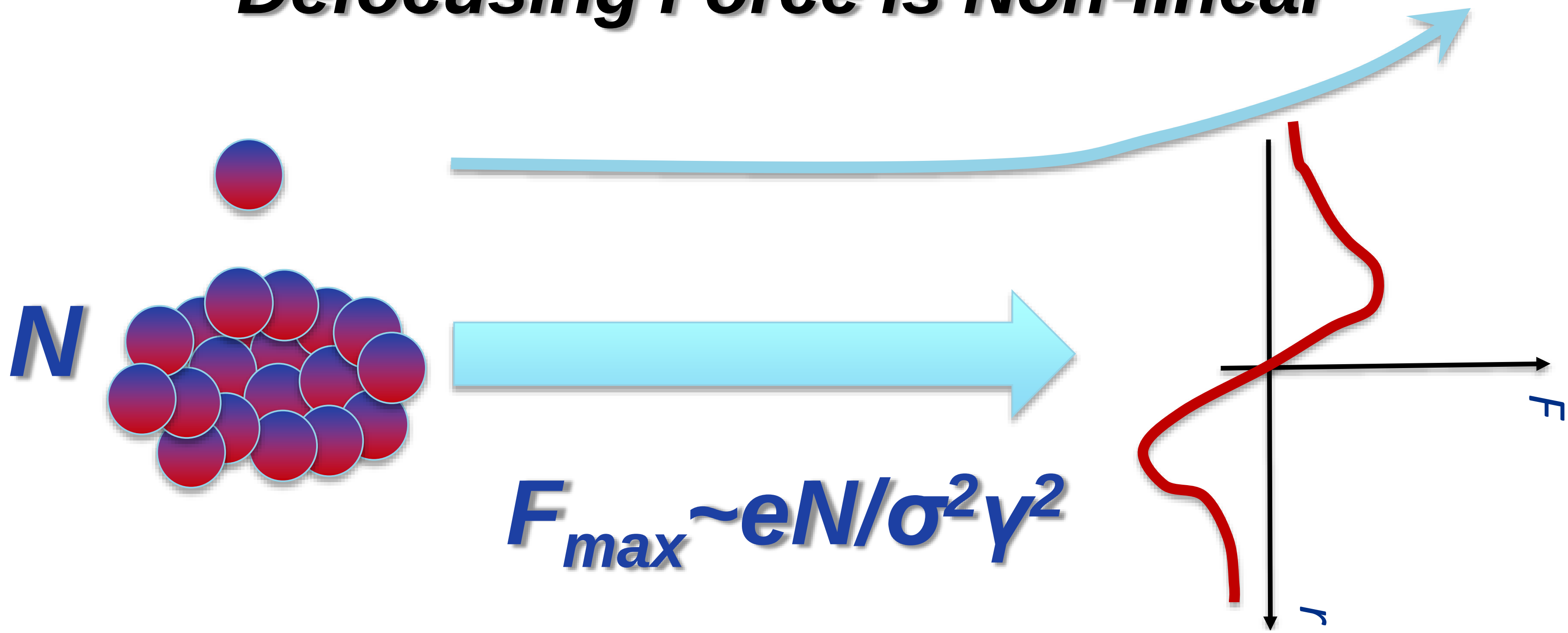


Net Force: Repels

$$eE - eE(v/c)^2 = eE\,(1 - \beta^2) = eE/\gamma^2$$

Intense Beams : Forces and Losses (2)

Defocusing Force is Non-linear



$$F_{max} \sim eN/\sigma^2\gamma^2$$

Space-charge effect (emittance growth, losses):

a) proportional to current (N)

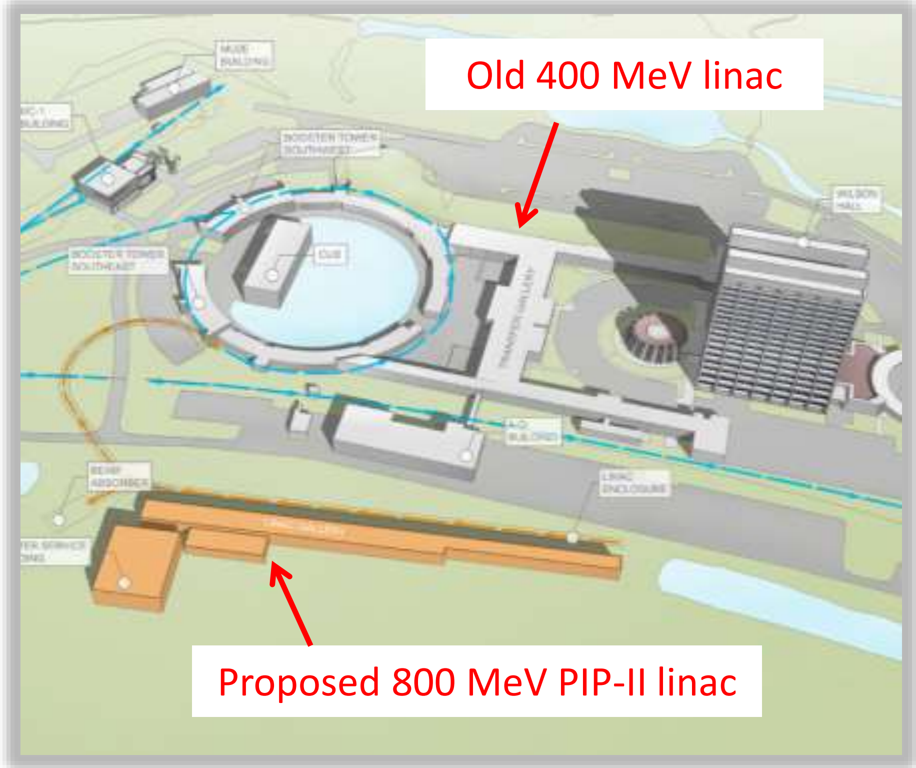
b) scales inversely with beam size (σ)

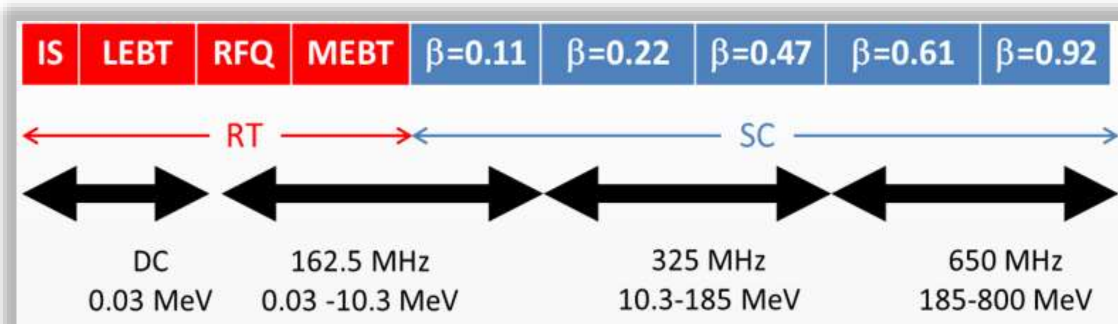
c) scales with time at low energies (γ)

Linacs 5-20 MeV/m
Rings 2-10 MeV/km

Proton Improvement Plan-II (PIP-II)

- **Key elements:**
  - Replace existing 400 MeV linac with an 800 MeV linac capable of CW operation.
    - Higher energy + painting = more beam in Booster
  - Increase Booster rate to 20 Hz
  - “Modest” improvements to Recycler and MI
  - Significant contributions from India
- **Goals:**
  - **1.2 MW @ 120 GeV for LBNF/DUNE**
  - Additional power:
    - 82 kW @ 8 GeV
      - Neutrinos (and kaons?)
    - ~100 kW @ 800 MeV
      - Arbitrary bunch structure
      - Muons (*mu2e**)





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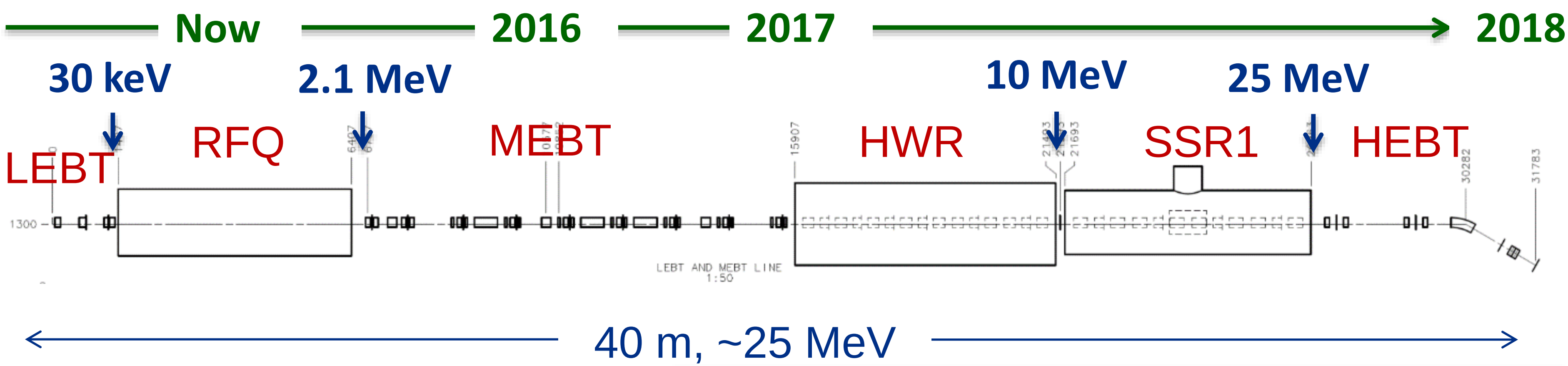
PIP-II Performance Goals

Performance Parameter	PIP	PIP-II	
Linac Beam Energy	**400**	**800**	**MeV**
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.6	msec
Linac Pulse Repetition Rate	15	20	Hz
Linac Beam Power to Booster	4	18	kW
Booster Protons per Pulse	**4.3×10^{12}**	**6.5×10^{12}**	
Booster Pulse Repetition Rate	15	20	Hz
Booster Beam Power @ 8 GeV	80	160	kW
Beam Power to 8 GeV Program (max; MI @ 120 MeV)	32	80	kW
Main Injector Protons per Pulse	4.9×10^{13}	7.6×10^{13}	
Main Injector Cycle Time @ 60-120 GeV	1.33*	0.7-1.2	sec
LBNF Beam Power @ 60-120 GeV	**0.7***	**1.0-1.2**	**MW**
LBNF Upgrade Potential @ 60-120 GeV	NA	>2	MW

*NOvA operations at 120 GeV

PIP-II Project: CD-0 (2015), R&D Ongoing



Linac Front-End Test:

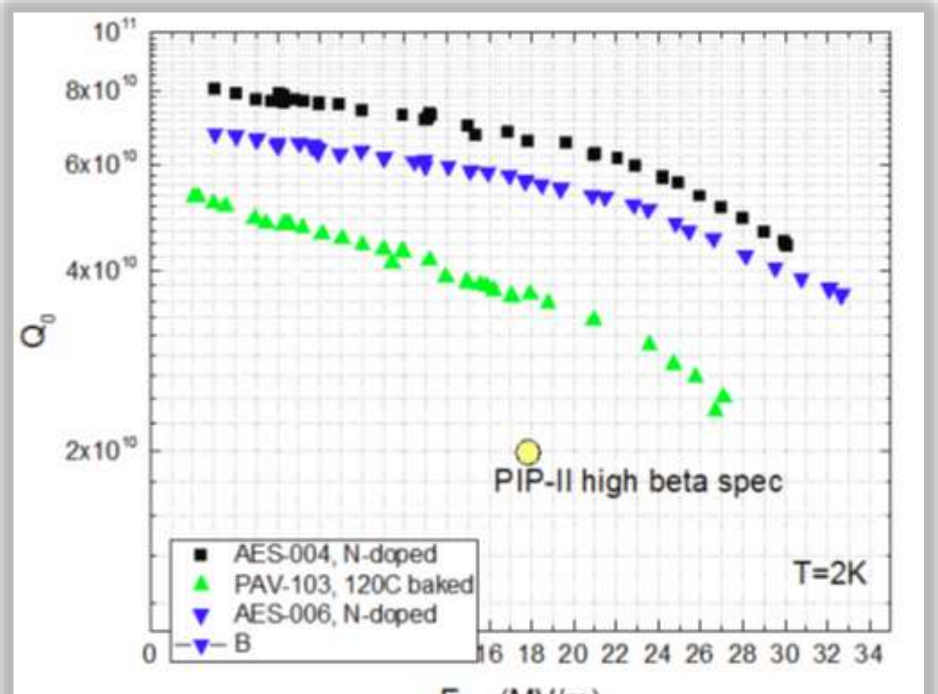
- *Challenging* : RT to SC transition at 2.1 MeV, 162 MHz CW beam chopper
- *Achieved:* 10Hz, 5mA (design) in 50 us pulses out of RFQ

Collaborators
- ANL: HWR
- LBNL:LEBT, RFQ
- SNS: LEBT
- BARC: MEBT, SSR1, RF
- IUAC: SSR1

PIP-II Project : R&D Ongoing

- SC RF Cavity developments: 5 different types @ 3 frequencies
  - 162.5 MHz *Half-Wave Resonators* design complete, cryomodule in production
  - 325 MHz *Single-Spoke Resonators (SSR1)* design is mostly complete (~90% in TC), production started
  - 650 MHz *High-Beta resonators* design is advancing well
  - Collaboration with Indian Institutions progresses

- High Q_0 SRF Research:
  - Nitrogen doping during cavity surface processing more than doubles Q_0 and reduces needed cryoplant capacity
  - Also found that fast cooling suppresses magnetic flux penetration to SC cavity and improves Q_0

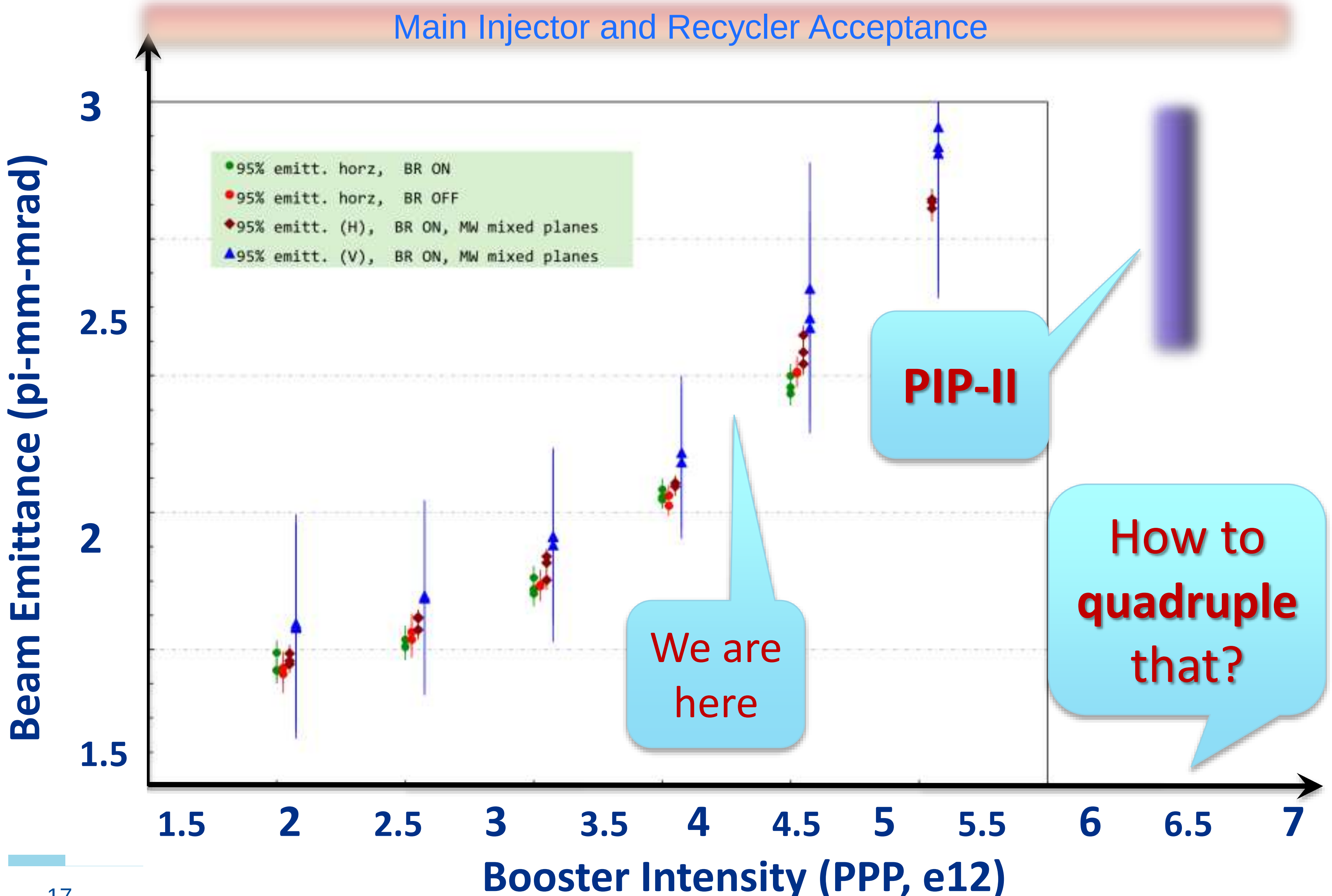


(A. Grassellino)

Next Upgrade of Accelerator Complex to Multi-Megawatt Beam Power Levels
2.4 MW + …after 2030

- We just started development of the concept and began corresponding R&D
- Key elements:
  - Replace Booster (it's a bottleneck)
  - **Affordable Cost !!!**
  - Use PIP-II and Main Injector
  - Develop multi-MW targets (P.Hurh)
  - Recycler might be kept, but *no Slip-Stacking:*
    - that means x4 increase in *protons per pulse*

Booster Bottleneck: Emittance vs Intensity, Losses



- To enable multi-MW beam power, losses must be kept well <<1% at the record high intensity:
  - e.g. tolerable radiation levels ***~ 1W/m***
  - 500 W in new Booster @ 320 kW → losses <0.16% (2% inj)
  - 3kW in Main Injector @ 2.4 MW → losses <0.12% (2% inj)
  - Present losses ~3-5% in Booster and MI synchrotrons
- Several approaches:
  - 8 GeV SRF linac:
    - Can cost be reduced? (1 GeV LCLS-II *1 B$*) → R&D
  - 8 GeV Rapid Cycling Synchrotron:
    - How to handle ***x4*** space-charge force? → R&D
  - Hybrid (e.g., 2 GeV Linac and 8 GeV RCS):
    - Won't it cost twice the RCS?

(How to Get Around) Space Charge Limit

- The maximum useful injected charge into the Booster is limited by the *space charge tune-shift*, which can drive harmonic instabilities.

total protons

"Bunch factor" = I_{peak}/I_{ave}
(Reduce with higher RF harmonics)

$$\Delta\nu \approx \frac{N r_0}{2\pi \epsilon_N \beta \gamma^2} F B \lesssim .3$$

normalized emittance
$\epsilon_N = \epsilon\beta\gamma = \text{constant}$

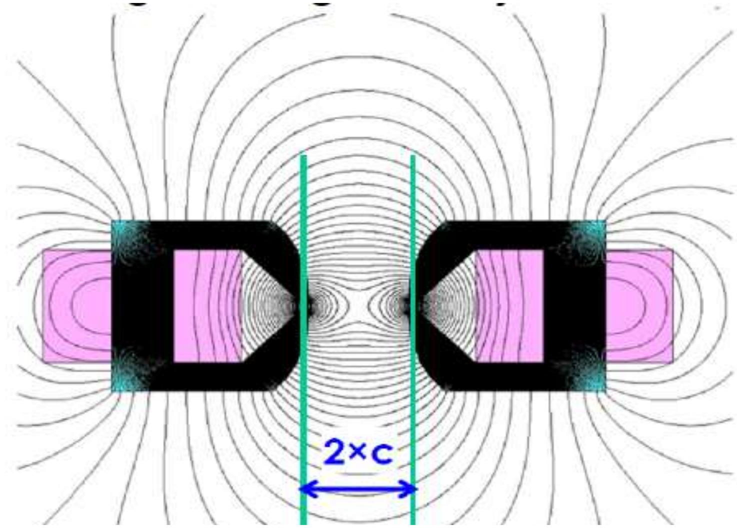
= 3 for 95% Gaussian emittance
1 for 100% uniform (painted) emittance

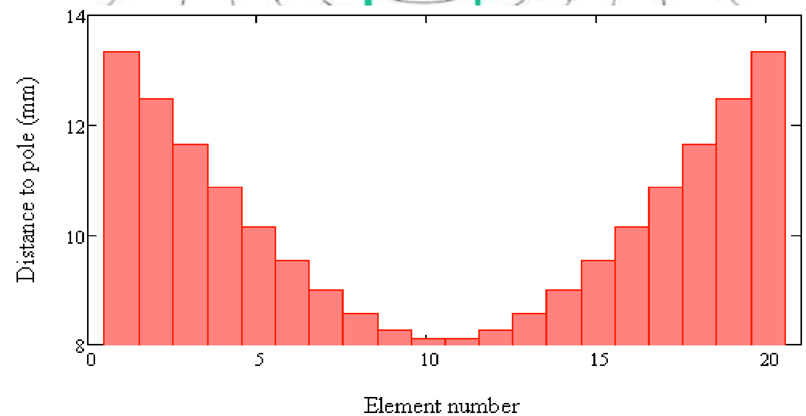
(if not straightforward solution – double the energy - then)

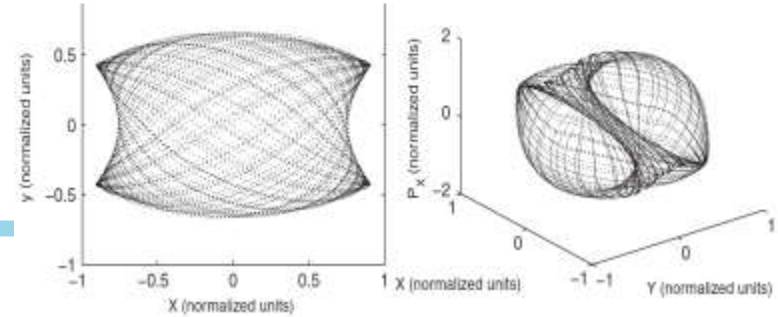
- Two novel approaches to increase the SC tune-shift:
  – "Integrable Non-Linear Optics"
  – Space-Charge Compensation with Electron Lenses
- Possibly augmented with Superperiodic Focusing Lattice and "flat long bunches" (multiple harmonics RF)

Integrable Optics with Non-linear Magnets

- Additional integrals of transverse motion possible:
  - Special NL magnets →
  - Special optics of the ring
  - Special longitudinal shape of the magnets (gap vs Z) →
  - Makes particle dynamics stable with very large tune-spread
    - Danilov, Nagaitsev, PRSTAB **13**, 084002 (2010) →



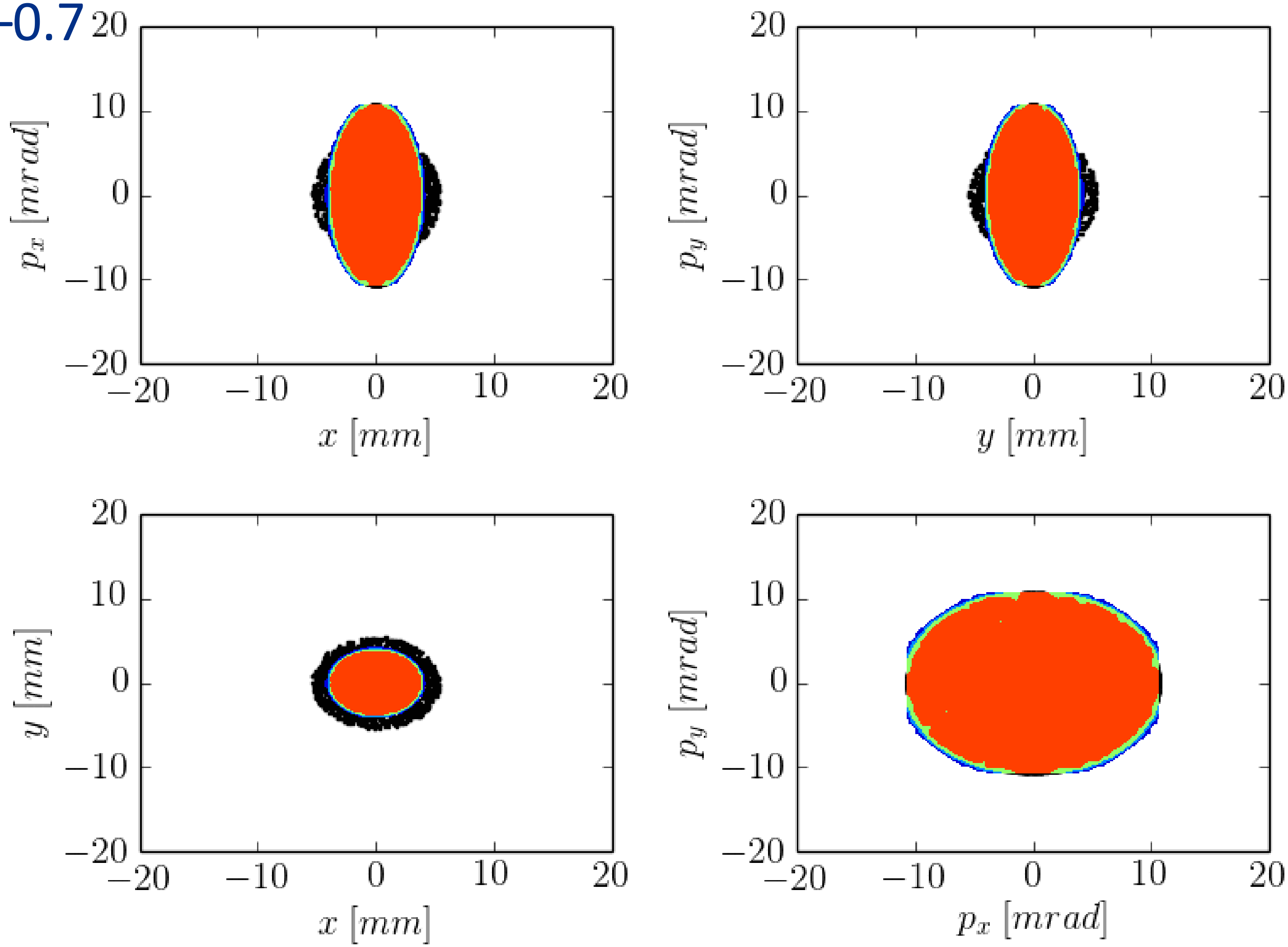




Space Charge Driven Halo in *Linear Optics*

- System: linear FOFO 100 A linear KV w/mismatch
- Result: quickly drives test-particles into the halo

$\Delta Q_{sc} \sim -0.7$

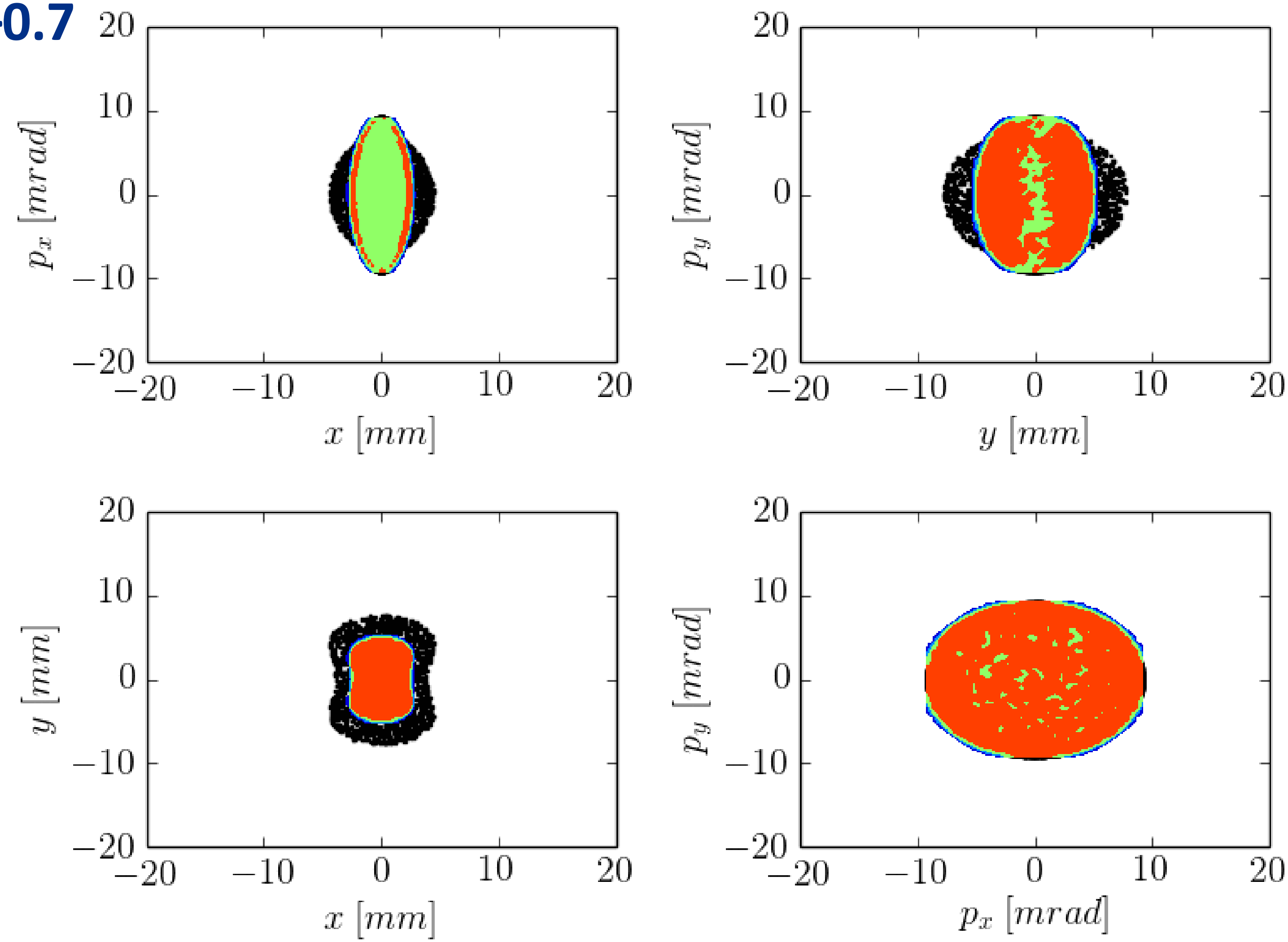


Tech-X, RadiaSoft simulation

Halo Suppressed in *NL Integrable Optics*

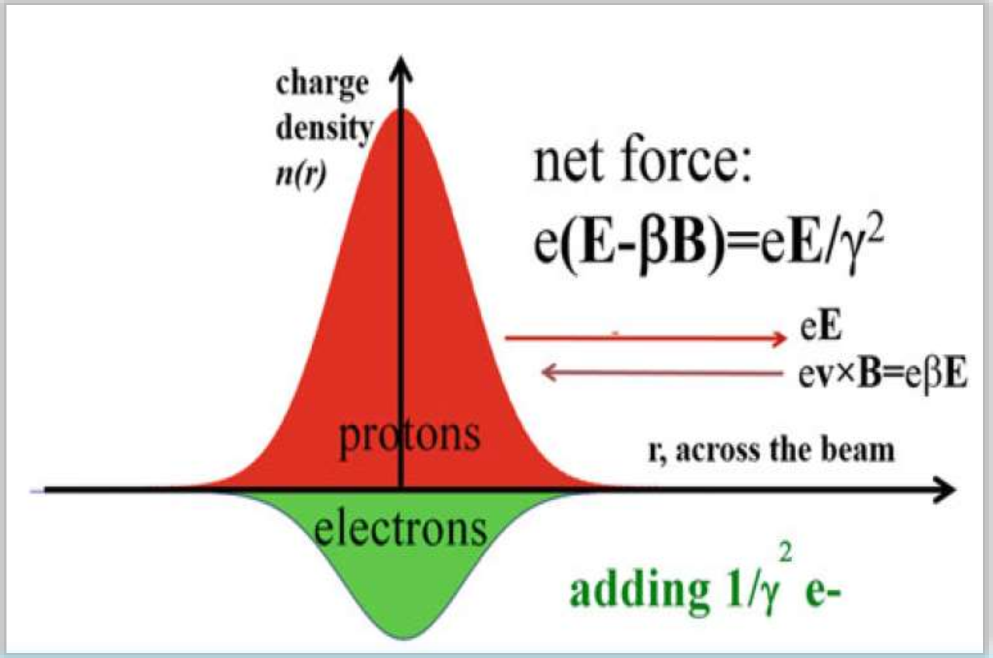
- System: linear FOFO 100 A linear KV w/mismatch
- Result: nonlinear decoherence suppresses halo

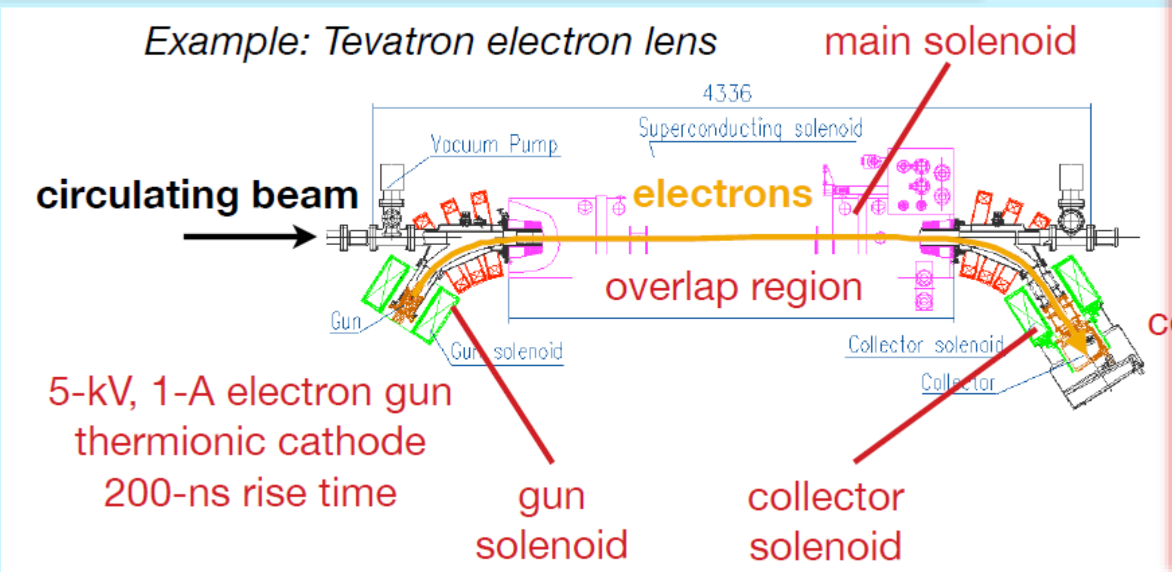
$\Delta Q_{sc} \sim -0.7$

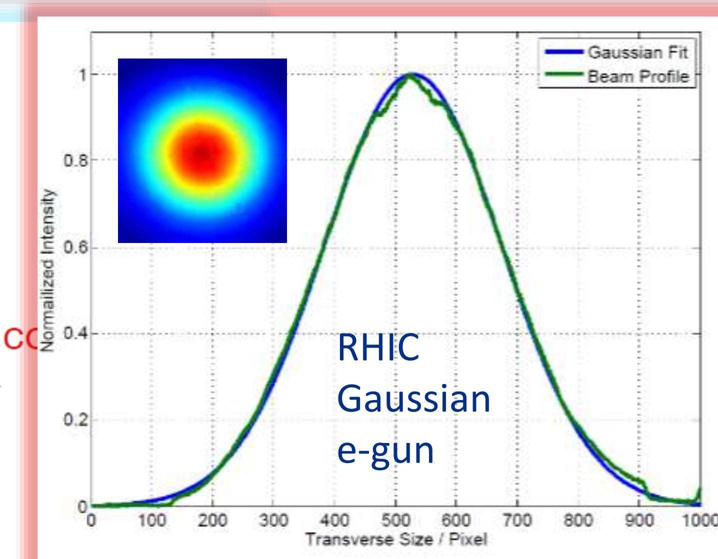


Tech-X, RadiaSoft simulation

Electron Lenses for Space-Charge Compensation





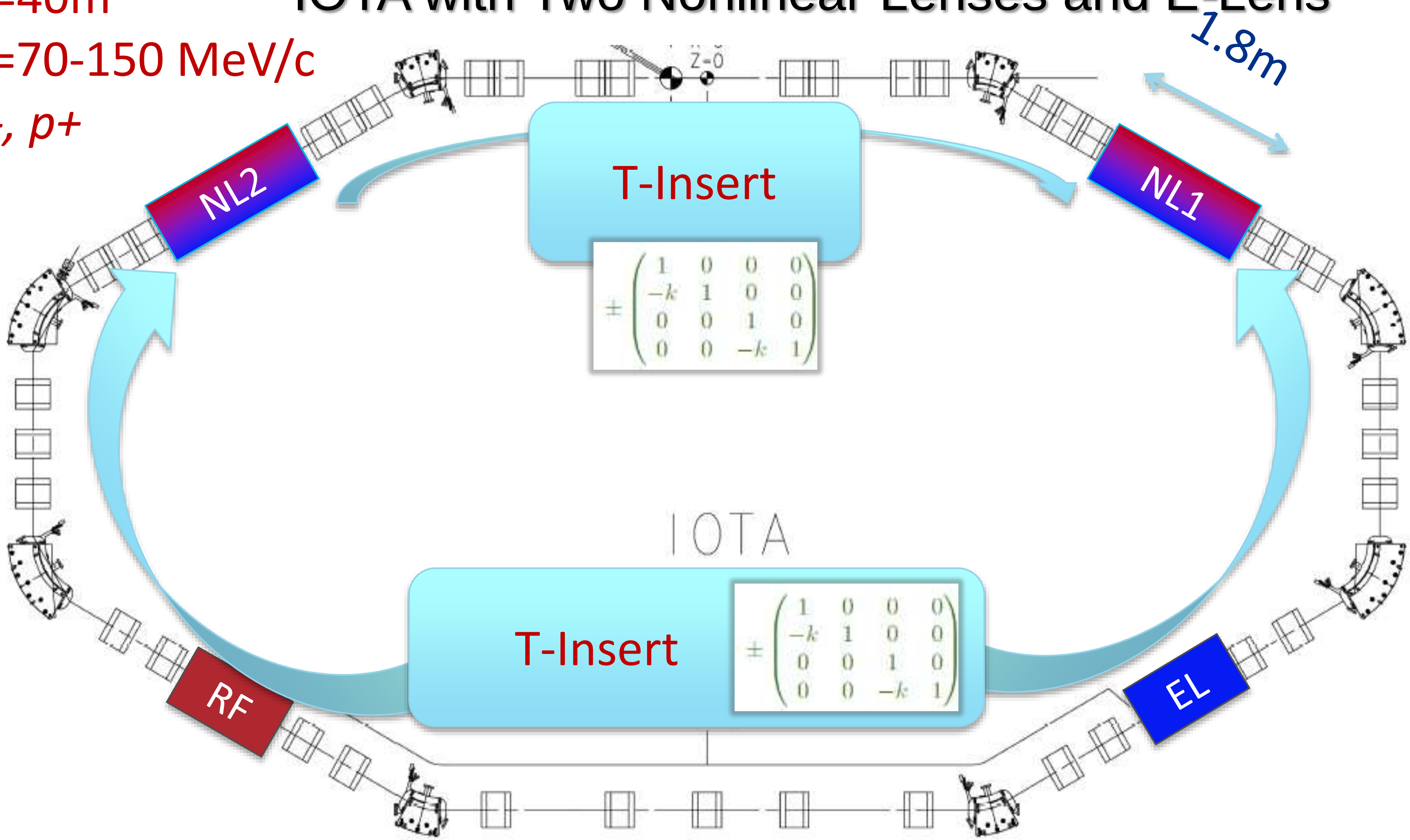


Both Nonlinear IO and E-Lens SCC work in Simulations!→ experimental verification at the

Integrable Optics Test Accelerator

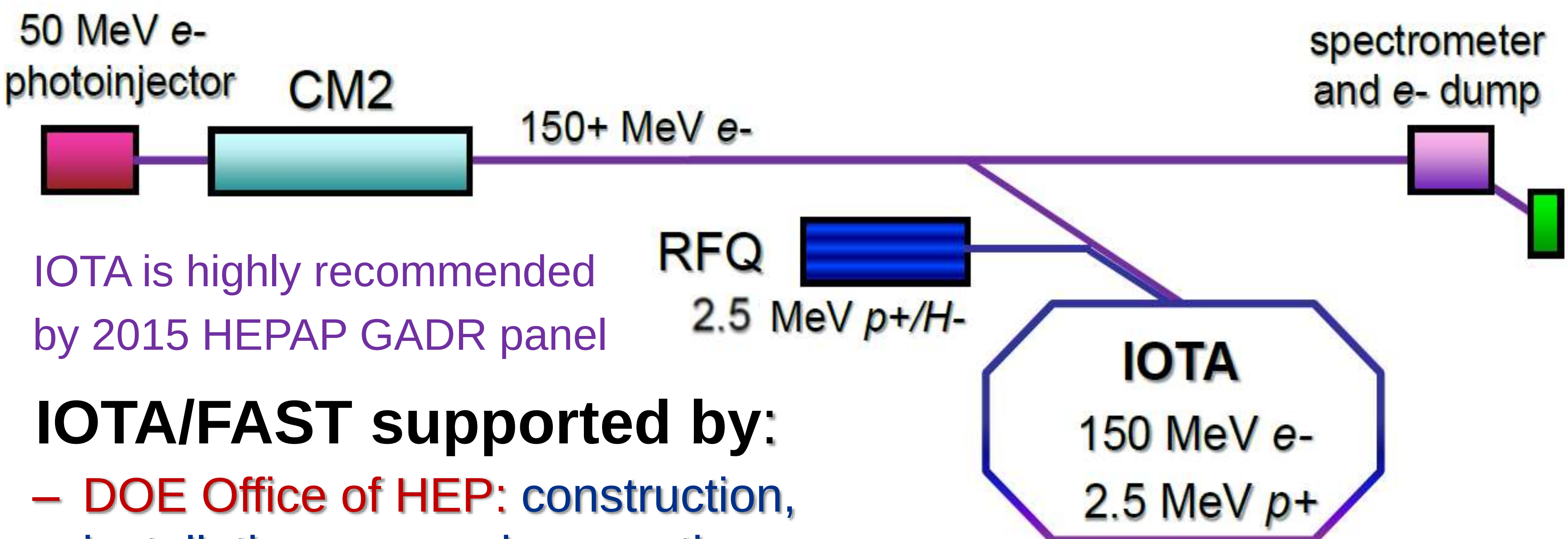
C=40m
P=70-150 MeV/c
e-, p+

IOTA with Two Nonlinear Lenses and E-Lens



To carry out R&D toward multi-MW upgrade..

- Fermilab constructing Accelerator Test Facility consisting of:
  - IOTA ring itself
  - Its two injectors (electron and proton) = FAST (Fermilab Accelerator Science and Technology) facility
  - Both occupy the 18,000 sq ft NML building

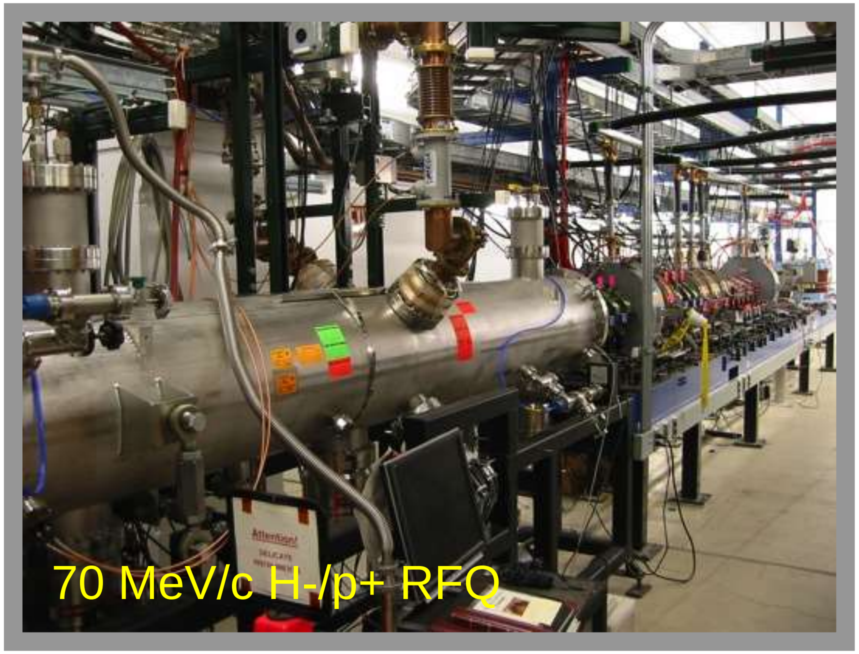


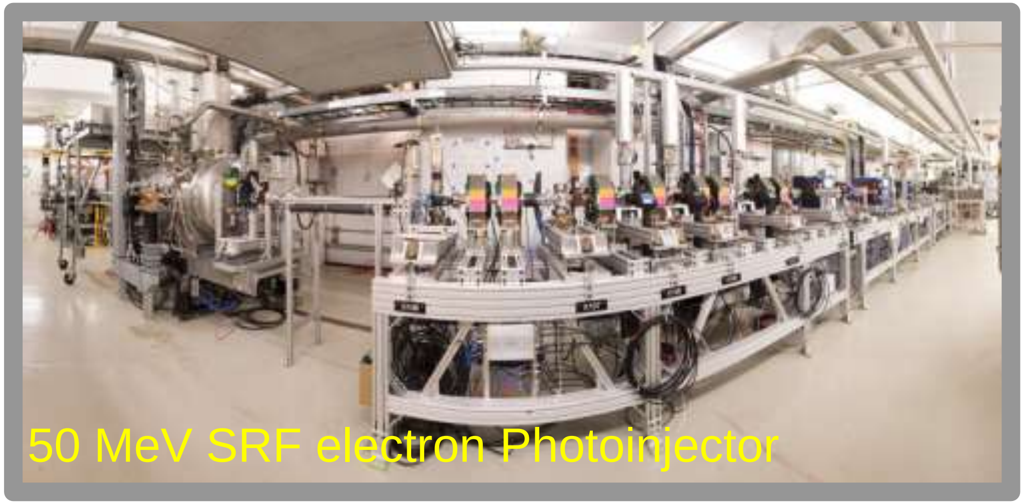
IOTA is highly recommended by 2015 HEPAP GADR panel

IOTA/FAST supported by:

- DOE Office of HEP: construction, installation, research, operations
- Collaborators (25): components, research

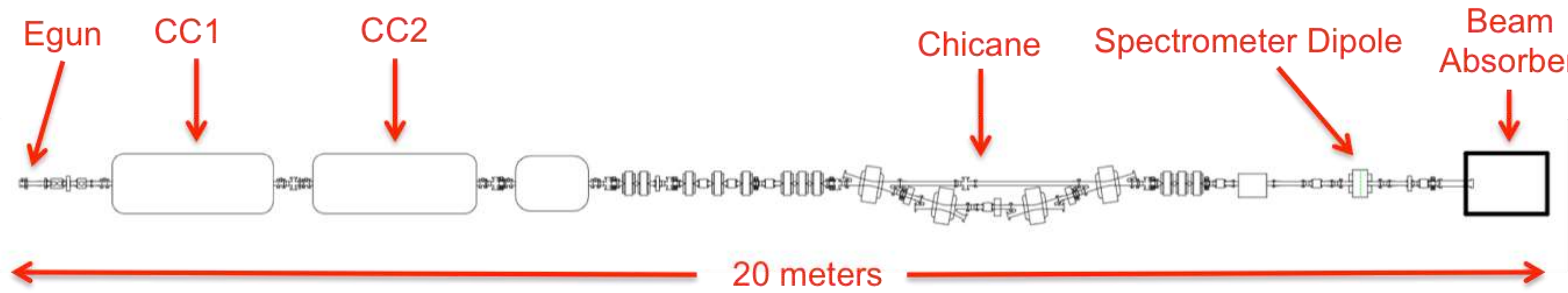

record gradient 31.5 MV/m
achieved in CM2
1.3 GHz SRF Cryomodule


70 MeV/c H-/p+ RFQ


50 MeV SRF electron Photoinjector

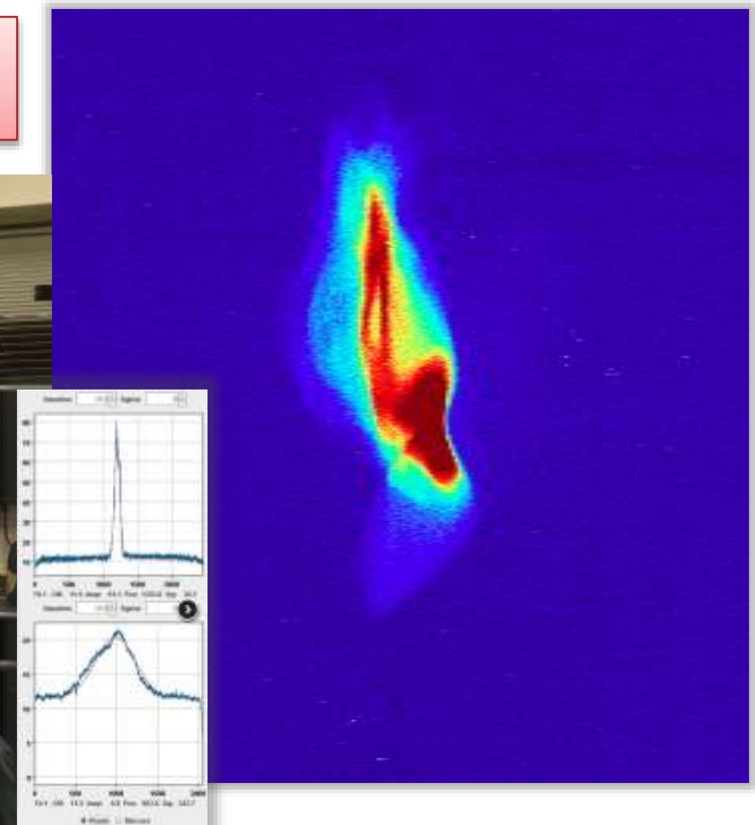

IOTA Ring Hall

May 2016 : IOTA Electron Injector 50 MeV



52.5 MeV e^- beam through FAST injector !

May 16, 2016: Beam accelerated by two 1.3GHz SRF Capture Cavities #1 and #2: 4.5 MeV (gun)+28MeV+20MeV



Summary

- Fermilab moves into the area of Intensity Frontier HEP to lead it
  - NuMI
  - LBNF/DUNE
- Its accelerator complex undergoes upgrades (Proton Improvement Plans):
  - achieved > 600kW on neutrino target (2016)
  - aims at 700kW in FY17 (PIP goal)
  - 1.2MW for LBNF/DUNE with PIP-II (800 MeV SRF Linac)
  - explore ways to get to 2.4MW+ after Booster replacement
- Extensive accelerator R&D program launched to address cost and performance risks:
  - PIP-II Front End facility, development of SRF cavities
  - IOTA ring novel space-charge mitigation methods
- Strong int'l collaborations formed (eg India) – *You're Welcome!*

Thanks for Your Attention !

Acknowledgements

David Bruhwiler, Paul Derwent, Steve Holmes, Valeri Lebedev, Sergei Nagaitsev, Bill Pellico, Eric Prebys, Cheng-Yan Tan, Alexander Valishev, Bob Zwaska